GAPP Year 2 Annual Report (Marks - Project GC03-404)

Title of Abstract
Influence of Sub-grid Variability on Snow Deposition and Ablation in North American Mountain Environments: Implications for Upscaling to Meso-scale Representations

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Introduction

The primary runoff generation zones of the Mississippi, Colorado, Columbia, Saskatchewan and Mackenzie drainages lie in the Western Cordillera and 40-90% of this runoff is generated by snowmelt. The reduction of shortwave reflectance (from 90% to 10%) and the thawing of frozen ground during ablation of the seasonal snowcover are significant to global climate and weather patterns. Many investigators have shown that basin-scale variability in snow deposition and melt is strongly influenced by the scale of variation in topography and vegetation and that this scale is usually 10s to 100s of meters, and, from the hydrologic modeling perspective, always sub-grid or sub-catchment. This snowcover variability is highly scale dependent and not well represented in regional and continental-scale models. An improved understanding of sub-grid variability will assist in assimilating remote sensing information to model operations, and assist in parameterizing basin-scale variability in regional and global scale models.

The processes controlling the rates and magnitude of snow deposition and ablation over complex topography and in and under vegetation canopies remains one of the greatest uncertainties in the operation of land surface schemes and hydrological models over mountainous regions. For instance, very few hydrological or land surface models distinguish between snow intercepted in forest canopies, and the surface snowpack sheltered under forest canopies. No climate or water model includes the effects of exposed shrubs in collecting wind-blown snow in the alpine zone or the development of large drifts in topographically sheltered areas; these effects transform shortwave and longwave radiative exchange above the snowpack and moderate turbulent exchange between the atmosphere and underlying snowpack. Land surface schemes have at best an ad hoc representation of snow cover development and depletion that does not well represent wind redistribution of snow or actual aerial albedo decay during melt and results in significant errors in surface energy balance calculations. Complex mountain terrain includes combined effects due to slope, aspect, terrain shelter, and vegetation structure that largely control both snow redistribution and drifting during the development of the snowcover, and variable patterns of snowcover energetics during melt. These effects are either poorly described or ignored in regional and global scale climate and hydrological models.

Project Goals

The proposed project will facilitate the identification of how the predictive accuracy of mountain snowcover representations in meso-scale models can be improved. Specifically, this project will investigate how snowcover distribution and energy balance terms differ with terrain and canopy structure, and with altitude and latitude. This information will be used to identify how parameterizations of both the development and melting of the seasonal snowcover can be applied at different spatial scales in heterogeneous landscapes. The minimum complexity required to capture the essential features of snow deposition and ablation over a complex, vegetated landscape will be identified.

Methods

The research objectives will be accomplished through complementary measurement and modeling programs. Field measurements will take place in three world-class experimental basins: Wolf Creek Research Basin (WCRB) in the Yukon Territory (Canada), the Reynolds Creek Experimental Watershed (RCEW) in Idaho, and the Fraser Experimental Forest in Colorado (Fraser). These sites form a continental-scale transect that is representative of northern cordilleran mountains, semi-arid mountainous rangelands, and high-elevation Rocky mountain regions that comprise the headwaters of western North American river systems. Specific variables that will be measured at all sites include snow depth, snow water equivalent, total solar radiation, diffuse solar radiation, thermal radiation, air and soil temperature, wind speed and direction, and relative humidity. Spatially intensive manual sampling of snow and vegetation properties will also be coordinated and completed at all three sites during a series of focused field campaigns.

Process modeling will be done at point, small catchment, and basin scales at all three experimental areas. Fine-scale model results will be used to evaluate and verify upscaled model results, and to develop strategies for spatial aggregation. At the catchment scale (0.25 to 25 km^2) selected applications of detailed point models will be used to evaluate and validate grid-based model applications. Catchment scale modeling will be conducted using a similar suite of process models, but will be forced with generalized canopy, soil, and meteorological characteristics. Basin scale (25 to 2500 km^2) simulations will be limited to areas over which the grid-based catchment scale models can be applied to evaluate the effectiveness of using more aggregate modeling approaches. Spatial and temporal interaction of fine-scale processes will be modeled through process algorithms developed from the point and small scale modeling efforts, and evaluated against diagnostic observations.

Results and Accomplishments

This report covers the project activity accomplished during year 2. The activities during year two were dominated by focused field campaigns at WCRB and RCEW.

A field experiment was conducted at the Wolf Creek Research Basin, Whitehorse, Yukon Territory from March to June 2004. The experiment was to measure the spatial variability of snowmelt energy fluxes over montane shrub tundra in a high latitude site, and the physical controls on the fluxes and their variability over complex terrain. The experiment levered substantial direct and indirect financial contributions from the UK Natural Environment Research Council, the Canada Research Chair programme, the Canadian Foundation for Innovation, the Canadian Foundation for Climate and Atmospheric Sciences, the Province of Saskatchewan Science Innovation Fund and the Strategic Research Investment Fund of the Welsh Assembly Government. The experiment focussed firstly on the energy and mass balance of shrub tundra of various canopy heights by measuring latent and sensible heat fluxes above canopy and long and short wave radiation both above and below canopy. Other measurements included wind speed, radiant surface temperature, air temperature, humidity, snow depth and density. The experiment focussed secondly on the variability of snow ablation and associated snow accumulation and melt energetics through infrared imagery of complex terrain, gridded surveys of snow water equivalent, specialised irradiance observations, helicopter-based images of snow covered area and vegetation-induced shadows, and helicopter-based vertical gradients of air temperature and humidity. To conduct these measurements a field tent camp was established in a remote section of the Yukon and personnel were supported there for their scientific studies. Data were retrieved and archived and the camp was removed and the site cleaned after use. This completes the Wolf Creek observational stage of this study.

At RCEW, the field campaigns focused on measurements in three vegetation types: aspen, conifer (dominated by fir), and big mountain sagebrush. Detailed sub-canopy solar and thermal radiation measurements in the aspen grove, conifer stand, and big mountain sage site were completed at several times throughout the snow season. Radiation was measured at both random locations within each vegetation type and in cardinal directions from a particular tree or shrub. Detailed snow depth and density transects in the different vegetation types were also completed. Infrared pictures were taken in the different vegetation types in order to better understand temperature variation between snowpack and vegetation both spatially and temporally. Detailed vegetation data was collected in the sheltered aspen grove and coniferous stands to better understand the sub-canopy solar and thermal radiation measurements taken at these sites. Tree trunk surface and internal temperatures were measured in both the aspen and conifer stands using several thermocouples. Snowdepth and density were measured over the entire basin at several times throughout the snow season in order to track accumulation and for modeling purposes.

Intensive automated data collection continued at RCEW during year 2 including basic micrometerologic data and eddy covariance data. The additional micrometerological stations installed during year 1 were closely monitored and, in some cases, modified to ensure data quality during year 2. A 15-m tower consisting of three measurement levels (3-m, 9-m, and 15-m) was established within the aspen grove to characterize vertical variation of wind speed and direction, air temperature and humidity, and canopy surface temperature through the aspen canopy. Solar radiation and snowdepth are also measured at the tower site. Two eddy covariance (EC) systems were established during year 2. One is located in an aspen grove and the second is in an open site. The sites consist of a 3-D sonic anemometer, an infrared gas analyzer, a net radiometer, and an air temperature and humidity probe. The EC instrumentation collects 10 Hz data in order to allow one to determine latent heat flux, sensible heat flux, and carbon flux after data corrections.

A PhD student, funded through this project, has completed one year of course work and has begun work on her dissertation. The topic of her dissertation research includes investigating eddy covariance measurements of sensible and latent heat flux over snow at RCEW, how these measurements vary with vegetation type, how these measurements compare to modeled values, and how these measurements compare to the EC measurements taken at Fraser and WCRB.

Variability of snowmelt in high latitude mountain environments

The energetics and mass balance of snowpacks in the pre-melt and melt period were examined for 10 years in a high latitude mountain catchment: Wolf Creek Research Basin, Yukon Territory, Canada. Pre-melt snow accumulation was strongly depleted by intercepted snow sublimation in the forests and blowing snow in the alpine tundra but not significantly affected by the small elevational gradients in snowfall. As a result the maximum pre-melt SWE was found in the mid-elevation shrub tundra, which was roughly double that of the alpine tundra or forests. Elevation had a strong effect on the initiation of melt with the forest melt starting on average 16 days before the shrub tundra and 19 days before the sparse tundra. Mean melt rates showed a maximum in middle elevations and increased from 860 kJ/day in the forest to 1460 kJ/day in the alpine tundra and 2730 kJ/day in the shrub tundra. The forest canopy reduced melt while the shrub canopy enhanced it relative to the sparsely vegetated alpine tundra. Duration of melt was similar in the forest and shrub tundra at 20 days while the alpine tundra was shorter at 13 days; the differences due to differing snow accumulation and melt rates. The greatest year to year variability in the timing and rate of melt compared to the other sites was found in the shrub tundra, where the influence of shrub canopy on snowmelt energetics depended on snow depth and insolation. Differences in melt rate between alpine and shrub tundra were reduced in periods with high snow accumulation or extensive cloudy periods. The results show that in high latitude mountain catchments snowmelt rates are strongly influenced by both elevation and vegetation but year-to-year variations in weather substantially alter the effect of these factors.

Role of Shrub Tundra in Mountain Snowmelt Generation

Shrub tundra behaves in an intermediate manner between that of a grass and an open forest canopy with respect to its influence on snowmelt. As such it can accelerate snowmelt depending on the relative states of exposed shrub canopy and snow. Three seasons of observations using radiometers, eddy covariance and snow mass changes were made of arctic shrub tundra of varying canopy height and density. The major findings are:

i) snow accumulation in the shrubs is higher than in open tundra due to retention of snow by shorter shrubs and redistribution of snow to taller shrubs in windswept sites,
ii) medium to tall shrubs that can be buried by winter snow accumulation, 'spring up' as snow particle bonds fail due to weakening from wet snow metamorphism – this rapid emergence of vegetation completely changes the surface albedo and thermal and aerodynamic properties of the surface,
iii) the albedo of exposed shrub over snow is substantially lower over dense shrubs than open snowfields – in this sense the shrubs behave as a deciduous forest canopy.
iv) net radiation over shrubs is larger and more often positive than that over open snowfields due to lower albedo, however net radiation to snow under shrubs is much larger and more positive than that above the shrubs due to the downward net longwave flux direction.
v) the latent heat flux from snow under shrubs is not substantially different from that of open snowfields,
vi) sensible heat flux is controlled by the presence of 'warm' shrubs, particularly on clear days. Both upward sensible heat flow from shrub to atmosphere and a downward component that contributes to snowmelt are observed under strong solar radiation.
vii) snowmelt rates are generally enhanced under shrub canopies in comparison to open snowfields.

These results suggest that shrub tundra should be treated as a unique land surface in atmospheric and hydrological models.

Radiation Observations and Modeling - Shrubs

Snowmelt energy exchange under shrub canopies is strongly influenced by the transmission of short wave radiation through the canopy and the reflectance from snow under the canopy. Alder shrub tundra covering a valley bottom in the Wolf Creek Research Basin, Yukon Territory, Canada was studied. Shrub heights were approximately 2-m and the canopy was discontinuous and highly heterogeneous. Analysis of aerial photographs covering a 900 m^2 area indicated shrub and gap fractions of 0.4 and 0.6 respectively. Transmissivity observations were made using an array of upward looking pyranometers, 10 below canopy and one above canopy. These showed substantial diurnal and spatial variations, with only a small dependence on solar angle. Arially-averaged transmissivity through the shrub canopy ranged between 0.05 and 0.95, with a mean of 0.43, increasing under overcast conditions. Radiative transfer was modeled by segregating the surface into three dynamic fractions: shrub, gap and shaded gap. The shaded gap fraction was derived by simulating the shadows generated by the shrubs, for which measured distributions of shrub height and width were made. Transmissivity through shrub canopy was calculated for both shrub and shaded gap fractions. Net shortwave calculations were completed by applying observed albedo values to each of the three fractions. The resulting arial transmissivity and albedo, are between those expected for pure snow and pure shrub surfaces and a function of both PAI and shrub canopy gap structure.

Radiation Observation and Modeling – Longwave and Shortwave Radiation in Mountain Environments

At high latitudes, net longwave radiation provides an important contribution of radiant energy to snow due to the low solar elevation and the high albedo of snow. The effect is magnified in mountains due to shading and longwave emissions from the complex topography. This study examines incoming long-wave radiation to snow surfaces in the mountainous, sub-arctic Wolf Creek Research Basin, Yukon Territory, Canada during the springs of 2002 and 2004. Incoming longwave radiation was estimated from standard meteorological measurements and topography by segregating radiation sources amongst clear-sky, clouds and surrounding terrain. A sensitivity study was conducted to detect the atmospheric and topographic conditions under which emission from adjacent terrain significantly increases the longwave irradiance in complex topography. The total incoming longwave radiation to a surface was found to be much more sensitive to sky view factor, than to the temperature of the emitting terrain surfaces. A variation of Brutsaert's equation was found to effectively simulate incoming longwave radiation under clear-sky conditions for hourly time steps using temperature and humidity. Longwave emission from clouds, which raise longwave emissions above that from clear skies by 16% on average, were best-estimated using only daily atmospheric solar transmissivity and hourly relative humidity. An independent test of the estimation procedure was conducted using observations from near Saskatoon, Saskatchewan, Canada, and indicated that the calculations are robust in late winter and spring conditions.

Shortwave radiation varies strongly with slope, aspect and shading by remote topography in mountain environments, and this has profound influences on surface energy and water balances. A parametrization has been developed for the average and variance of incoming shortwave radiation over mesoscale regions of complex topography. This has been evaluated in comparison with high-resolution distributed simulations for Wolf Creek (Yukon Territory), Reynolds Creek (Idaho) and Maroon Creek (Colorado, chosen as an area of particularly steep and anisotropic topography). Topographic shading has also been investigated for mountainous regions in North Wales and the French Alps.

Snow Surface Temperature Observation and Modeling

The longwave radiant temperature of a snowpack is an important variable in energy balance calculations of snowpack energetics and as a lower boundary condition for the atmosphere over snow. It forms the basis for calculations of longwave emission from the snowcover and a lower reference condition for calculations of sensible and latent heat flux. These calculations govern the coupled energy and mass balance equations that determine snow dynamics, particularly the energy state of snow, surface sublimation and snowmelt. Recent observations of snow surface temperature with longwave radiometers suggest that they remain significantly reduced from that of either the snowpack or air, in pre-melt and melting conditions. To describe these situations, a new, simple radiant temperature calculation for snowpacks is developed assuming thermodynamic equilibrium amongst net longwave, sensible heat and latent heat in a thin surface layer of the snowpack. Net shortwave, conductive fluxes and internal energy change are ignored. The model shows great skill in simulating the surface temperature of a grassland snowpack under ventilated conditions from -37 to +5 C. It has been further tested at moderate (Canadian Rockies) and extreme (Bolivian Andes) conditions and found, even in such extreme environments to provide good estimates under ventilated, stable conditions.

Turbulent Flux Observation and Modeling – high latitude tundra

There is increasing evidence that snowmelt rates are substantially different between shrub tundra and poorly vegetated tundra sites. Three calculation schemes were used to find the simplest model structures that could, without calibration, calculate snowmelt and surface energetics for open and shrub tundra. At a dwarf birch shrub site, the short canopy was buried completely by snow, suggesting that a relatively simple, continuous snowcover single source scheme could be appropriate. Such a scheme provided good simulations of net radiation, sensible and latent heat fluxes, and ultimately snow depth ($R^2 = 0.99$). At an alder shrub site, the tall discontinuous shrub canopy required a more complex model structure. A single source scheme using an aerially-weighted albedo from snow and tall shrub cover melted snow faster than was observed. A more complex dual source scheme with explicit representation of both shrub canopy and snowcover fractions reduced this error by one-third. However, net radiation at the snow surface was overestimated because radiative transfer through the tall shrub canopy was underestimated, and current work (see above) seeks to improve the calculation of this transfer. Turbulent transfer was well estimated by the dual source scheme and differed considerably from that for short shrubs or open snowcovers.

Investigators Meetings

The primary investigators and associated researchers met in March during one of the intensive field campaigns, at the spring AGU meeting in Montreal and again in December at the American Geophysical Union Meeting to coordinate research efforts and future field campaigns.

Future Work

Unfortunately the 2004-2005 snow season has yielded little snowpack and warm temperatures. In some instances snowpack is at levels less than 50% of normal. This has forced the research team to abandon intensive field campaigns at RCEW though 2-3 depth and density surveys will be conducted. Automated micrometeorologic data and eddy covariance data continues to be collected and analyzed. Data analysis and model improvements from data collected at WCRB, Fraser and RCEW during year 1 and year 2 will continue. Any future field campaigns will be focused on issues that arise from data analysis.

A technique for estimating the variability of shortwave radiation under forest canopies from hemispherical photography has been developed and is being evaluated in comparison with observations from radiometer arrays. Work has begun on developing a statistical parametrization of the radiative environment on forest floors (including forested slopes) using data from Lidar and aerial photography.

Publications from this project

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